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Vanderbeck et al.

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(54) **PERMANENT MAGNET PHASE-CONTROL MOTOR**

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(52) **U.S. Cl.** **310/261**; 310/268

(58) **Field of Search** .... 310/75 R, 79, 310/96, 100, 68 B, 156.53, 268, 261; 318/138, 254, 439, 727, 798; 416/1, 151, 32, 47, 155, 5, 141, 157 A, 157 R, 160, 165

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,867,715	A	7/1932	Seidel	
1,879,659	A	9/1932	Coolidge	
2,443,393	A	6/1948	Landgraf	244/17
2,495,433	A	1/1950	Troller	170/160.46
2,517,509	A	8/1950	Sikorsky	244/17.11
2,554,611	A	5/1951	Biermann	170/160.37
2,650,046	A	8/1953	Vanderlip	244/17.13
2,716,460	A	8/1955	Young	170/160.1
2,845,132	A	7/1958	Heckman	170/160.25
3,586,460	A	6/1971	Toner	416/144
3,588,273	A	6/1971	Kizilos	416/42
3,747,728	A	7/1973	Hollander	192/58 A
4,195,966	A	4/1980	Cornelius	416/18
4,591,313	A	5/1986	Miyatake et al.	416/155
4,648,345	A	3/1987	Wham et al.	114/338
4,655,685	A	4/1987	Fradenburgh	416/90 A
4,702,437	A	10/1987	Stearns, Jr.	244/17.11
4,930,988	A	6/1990	Griffith	416/114
5,255,871	A	10/1993	Ikeda	244/17.13
5,281,094	A	1/1994	McCarty et al.	416/147
5,409,183	A	4/1995	Gunsallus	244/17.13
5,480,284	A	1/1996	Wadia et al.	416/91
5,490,759	A	2/1996	Hoffman	415/10
5,584,655	A	12/1996	Deering	416/31
5,584,661	A	12/1996	Brooks	416/238
5,588,800	A	12/1996	Charles et al.	416/24
5,595,474	A	1/1997	Girard	416/1
5,626,312	A	5/1997	Head	244/75 R
5,704,567	A	1/1998	Maglieri	244/17.11
5,711,651	A	1/1998	Charles et al.	416/24
5,727,754	A	3/1998	Carter, Jr.	244/8

OTHER PUBLICATIONS

Computing Electromagnetic Fields for Research and Industry: major achievements and future trends. IEEE Transactions on Magnetics, vol. 32, No. 3, May 1996, pp. 627–630.

Shape Optimization of Electromagnetic Devices using Immune Algorithm. IEEE Transactions on Magnetics, vol. 33, Mar. 1997, pp. 1876–1879.

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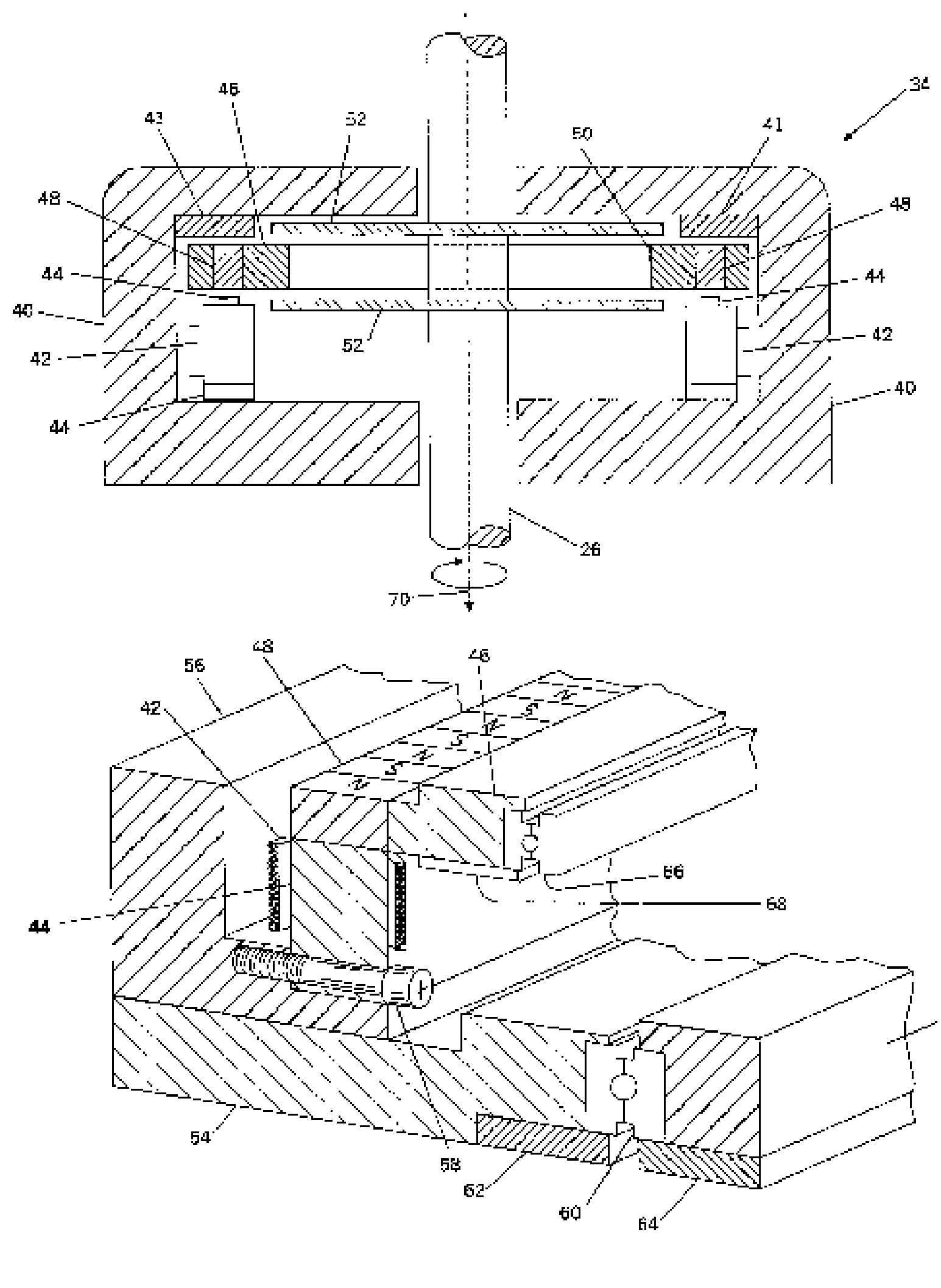
(57) **ABSTRACT**

A motor has a rotor for controlling a parameter of an instrumentality, such as a blade or a blade flap. The rotor is positioned about the drive shaft of the instrumentality and rotates at the same average angular velocity of the drive shaft. The instrumentality is controlled by applying to the instrumentality a physical displacement signal that is generated by the phase relationship of the rotor of the motor with respect to the angular position of the drive shaft. A plurality of permanent magnets proximate the periphery of the rotor cooperate with a plurality of stator polepieces and electromagnetic coils. The current flowing through the coils is reversed each time that the rotor advances by the angular space of one permanent magnetic pole. The strength and polarity of the current flowing through the coils controls the direction and displacement of the rotor with respect to a neutral phasing of the rotor with respect to the drive shaft.

10 Claims, 12 Drawing Sheets



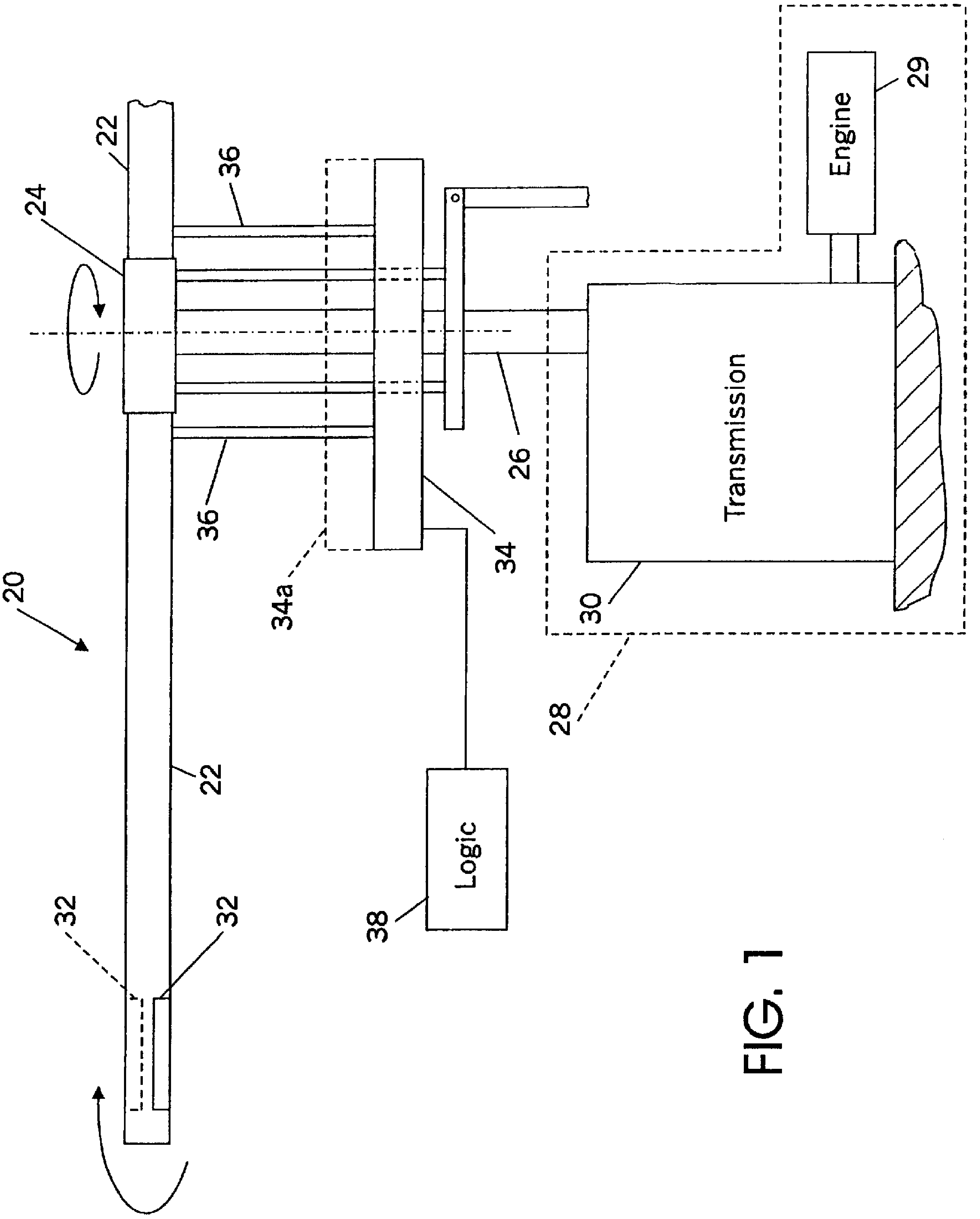

20
22
24
36
36
34a
34
26
38
Logic
28
30
Transmission
Engine
29
22
32
32

FIG. 1

FIG. 2

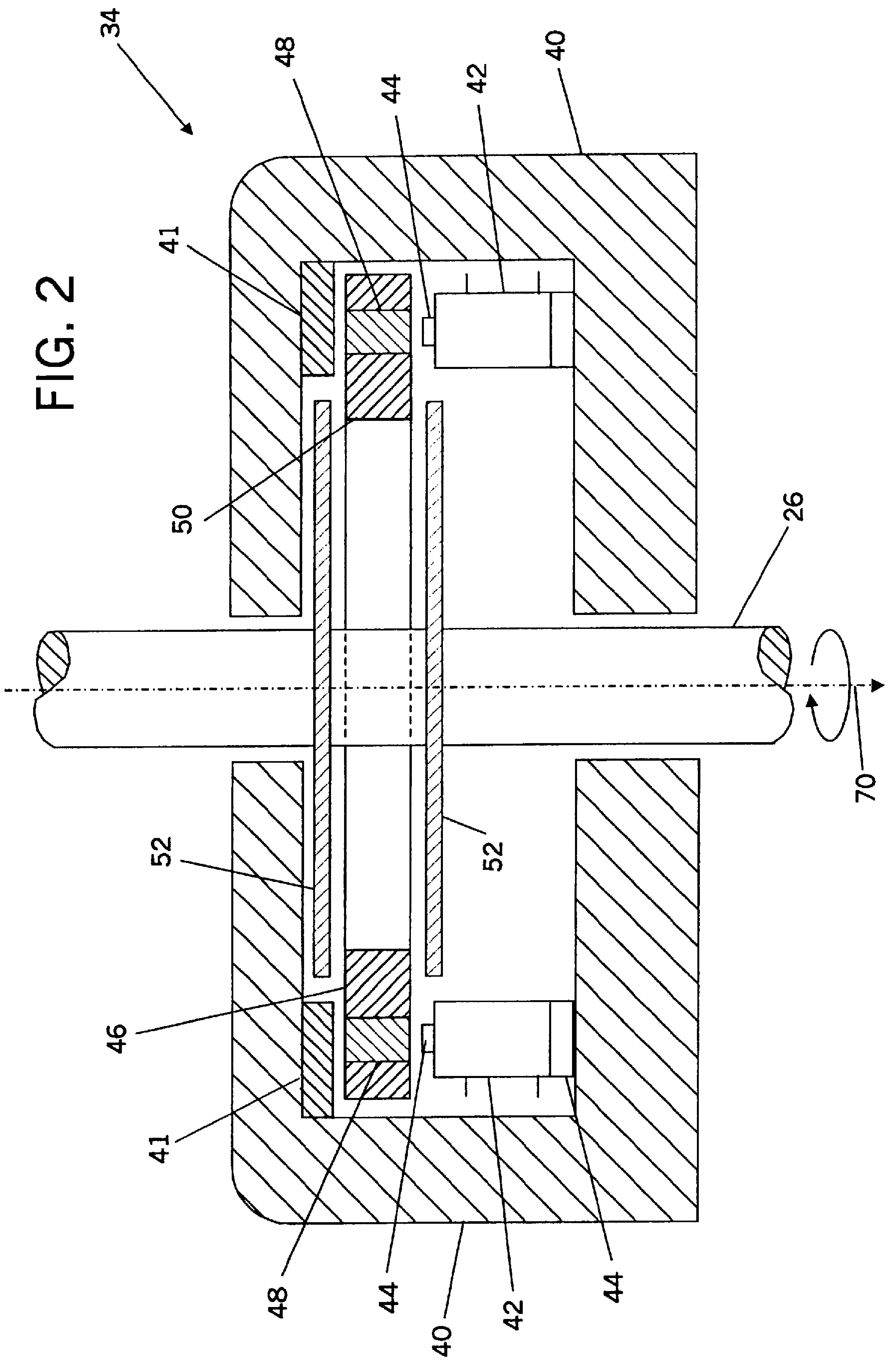


FIG. 3A

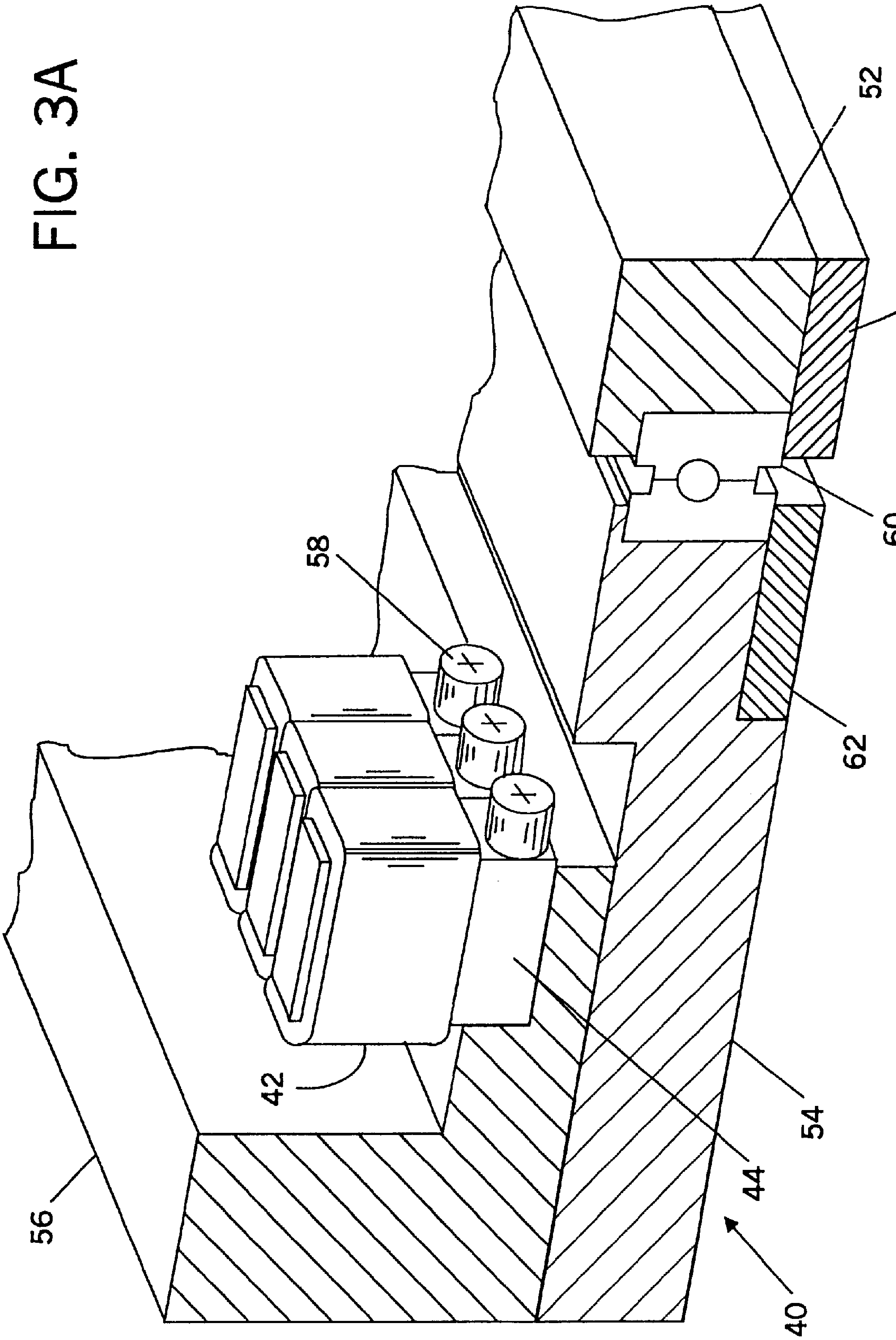


FIG. 3B

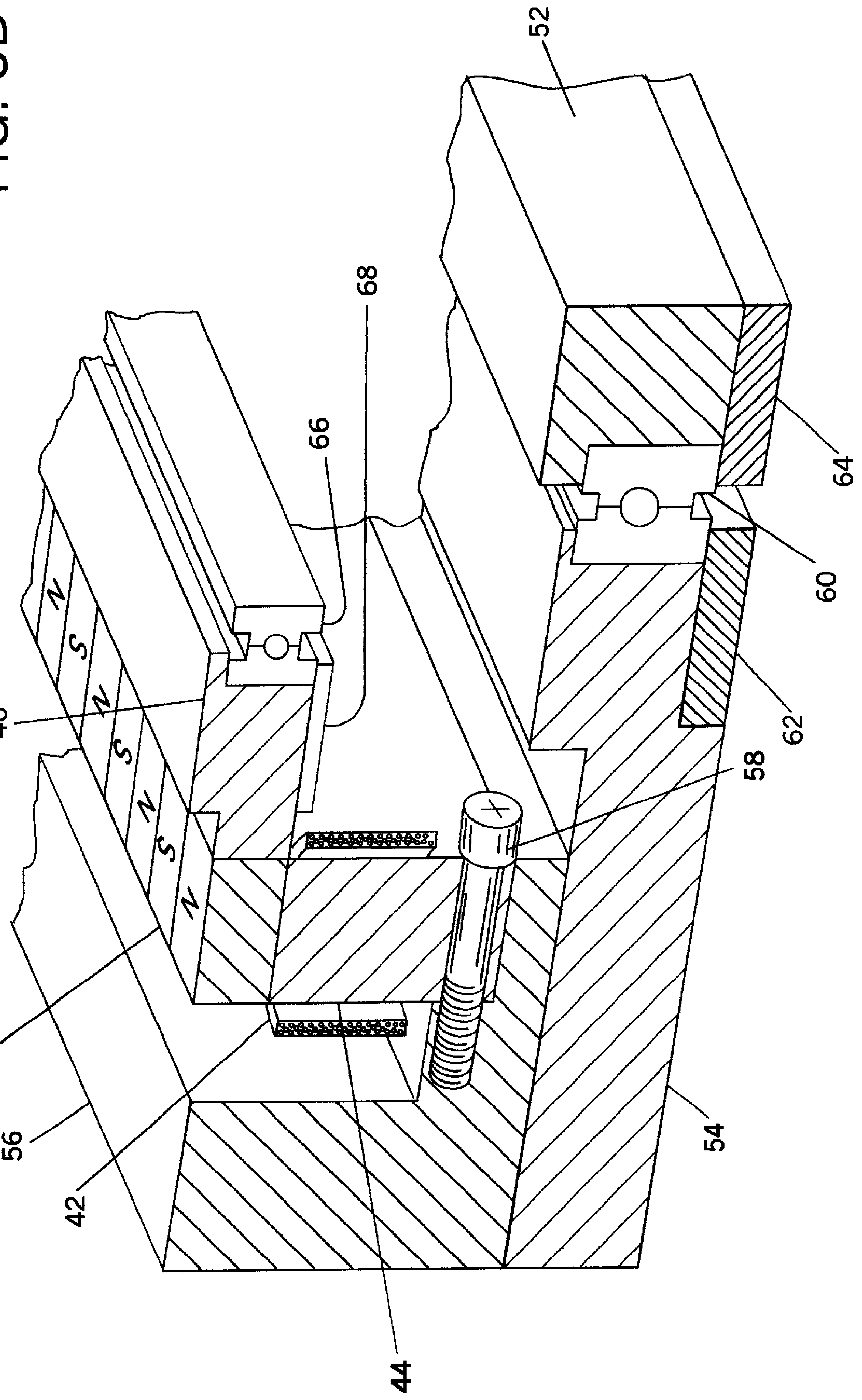


FIG. 3C

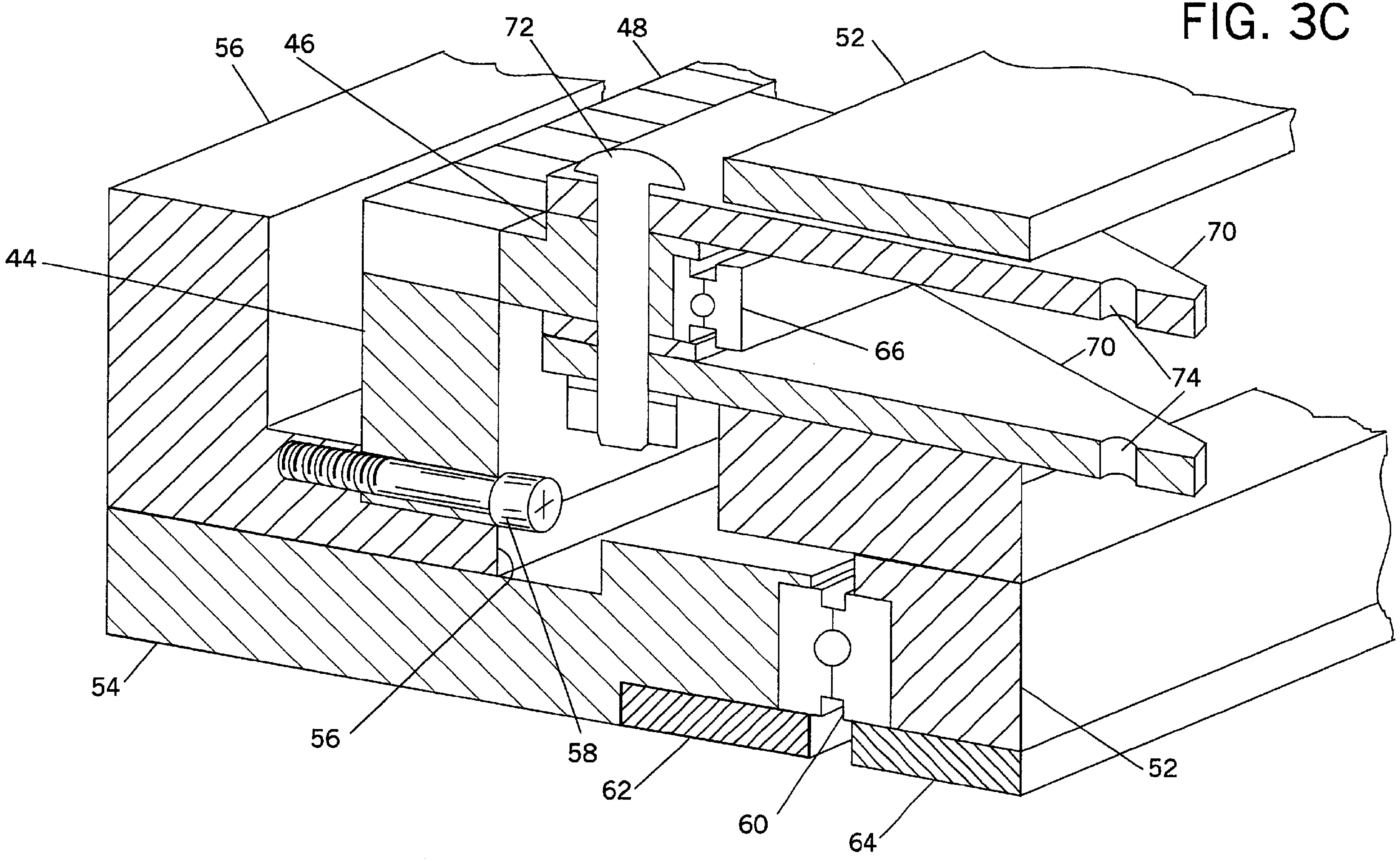
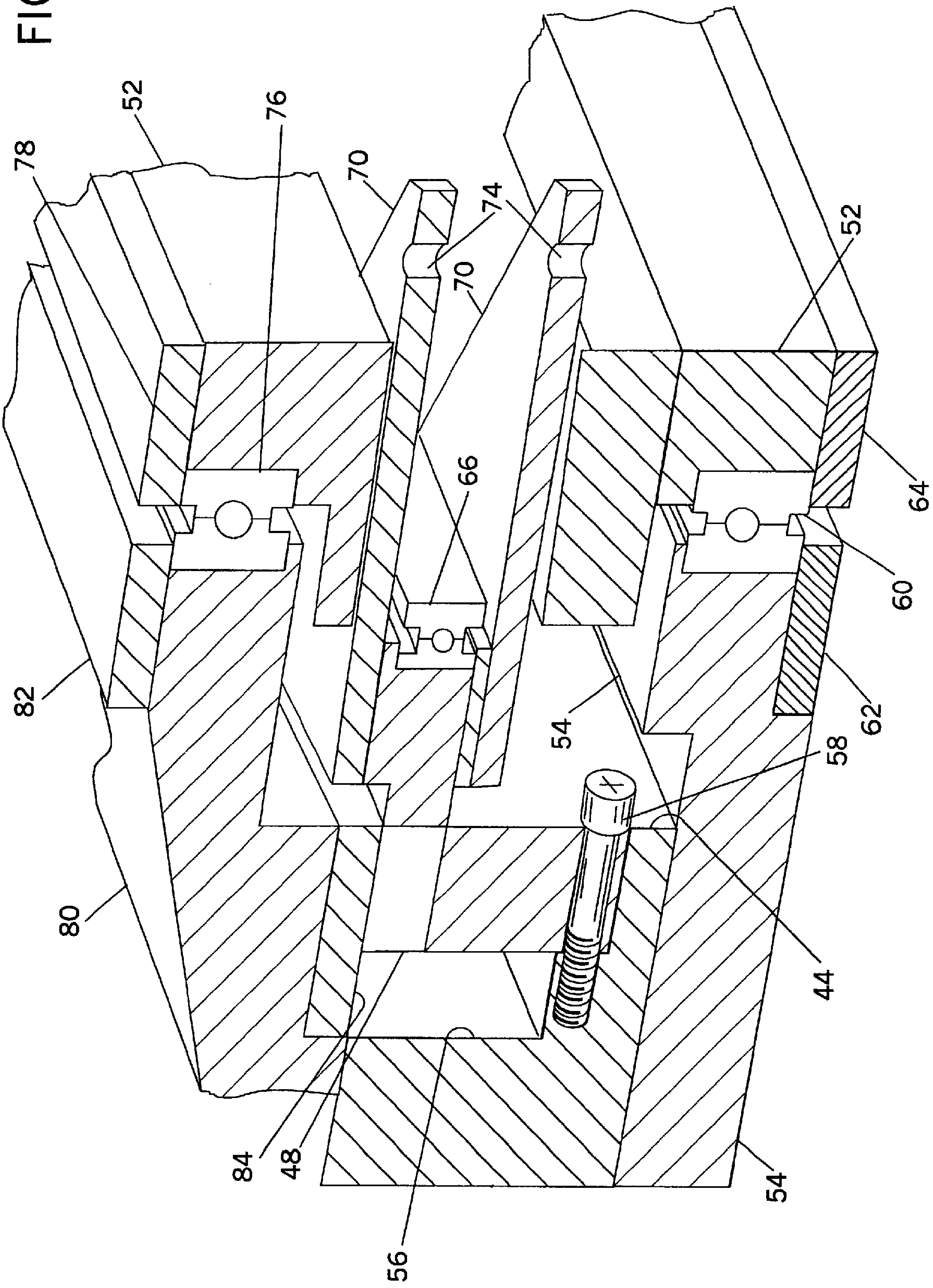


FIG. 3D



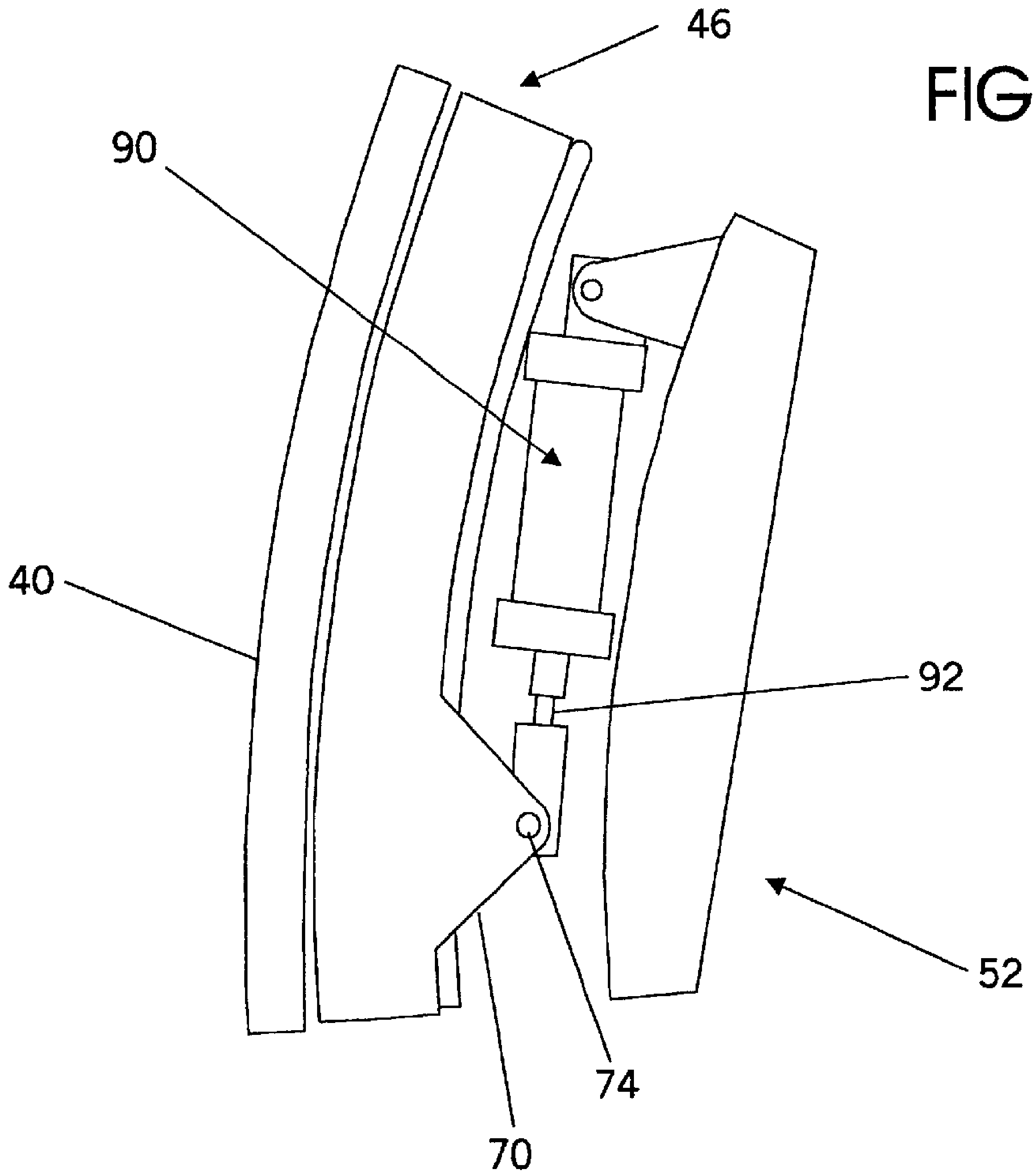


FIG. 4

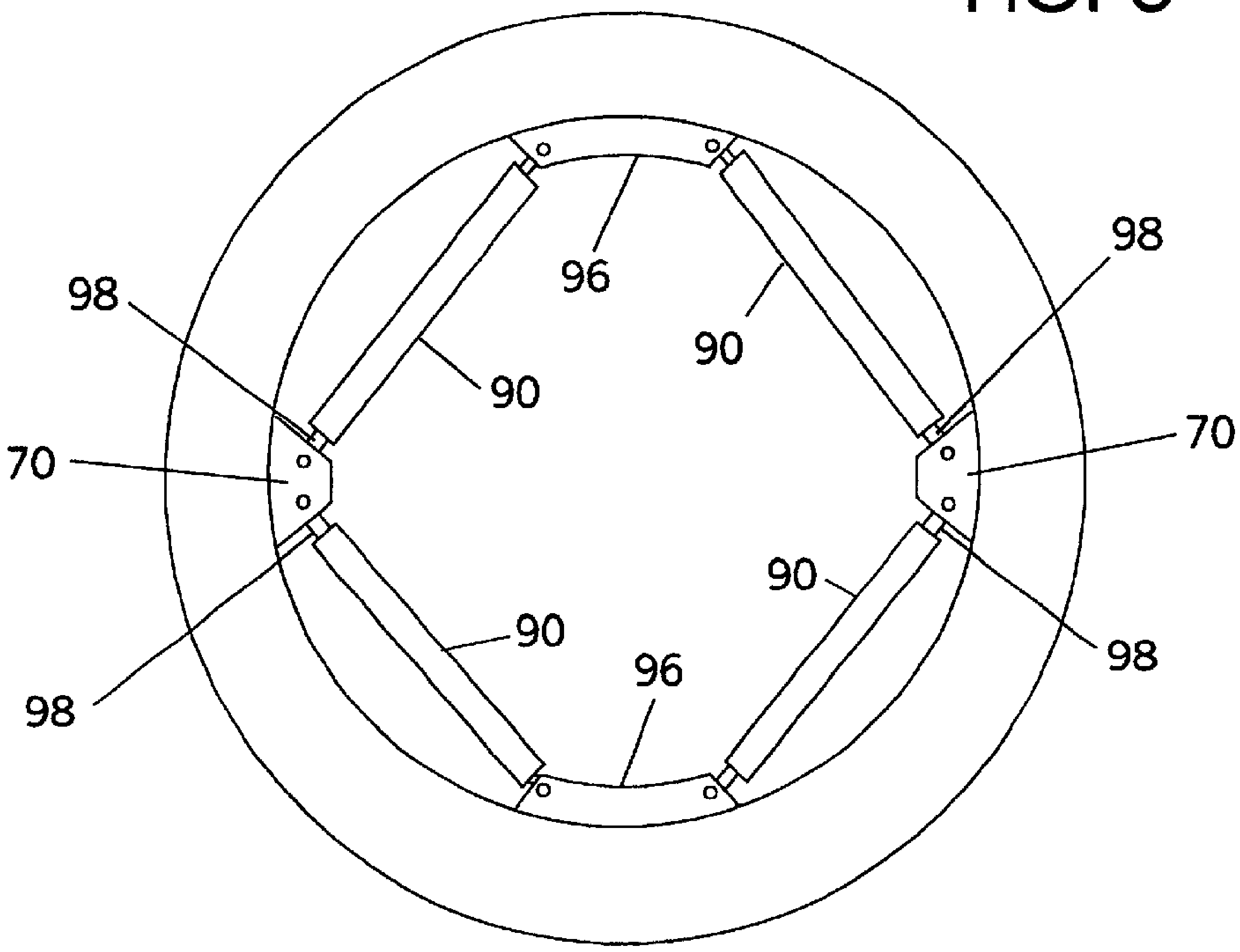
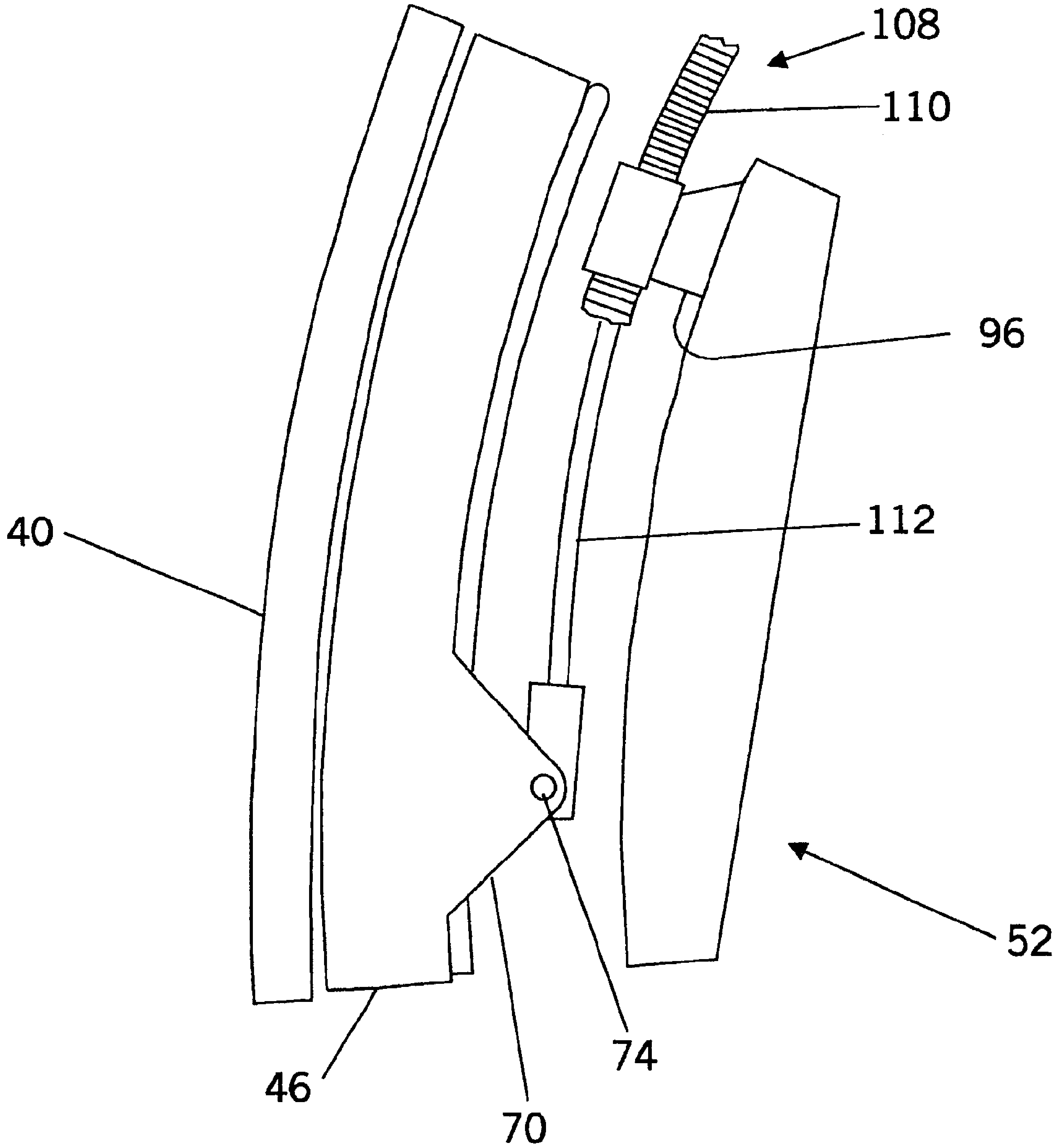


FIG. 5

FIG. 6



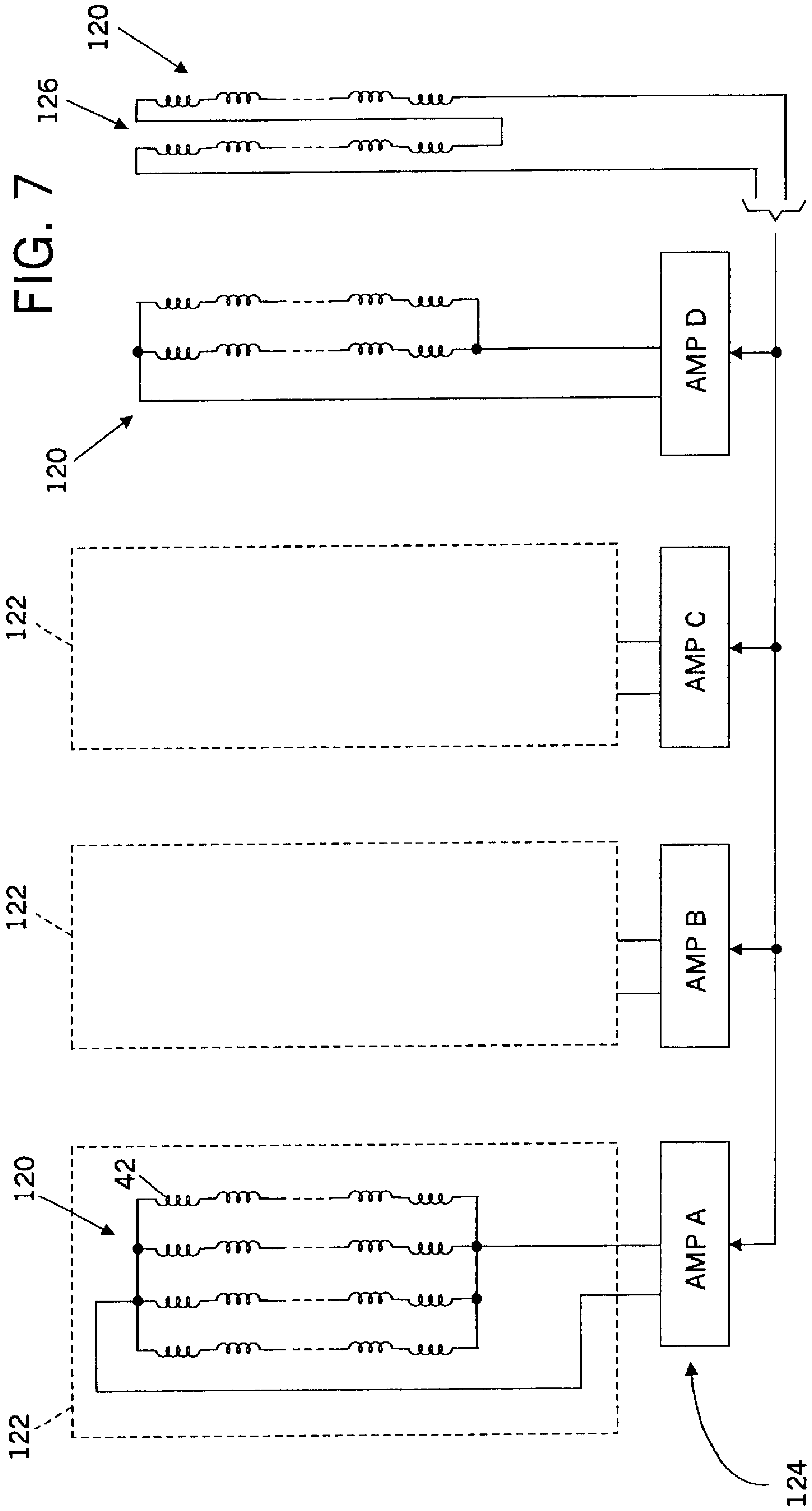


FIG. 7
120
126
120
AMP D
122
AMP C
122
AMP B
120
42
AMP A
122
124

FIG. 8

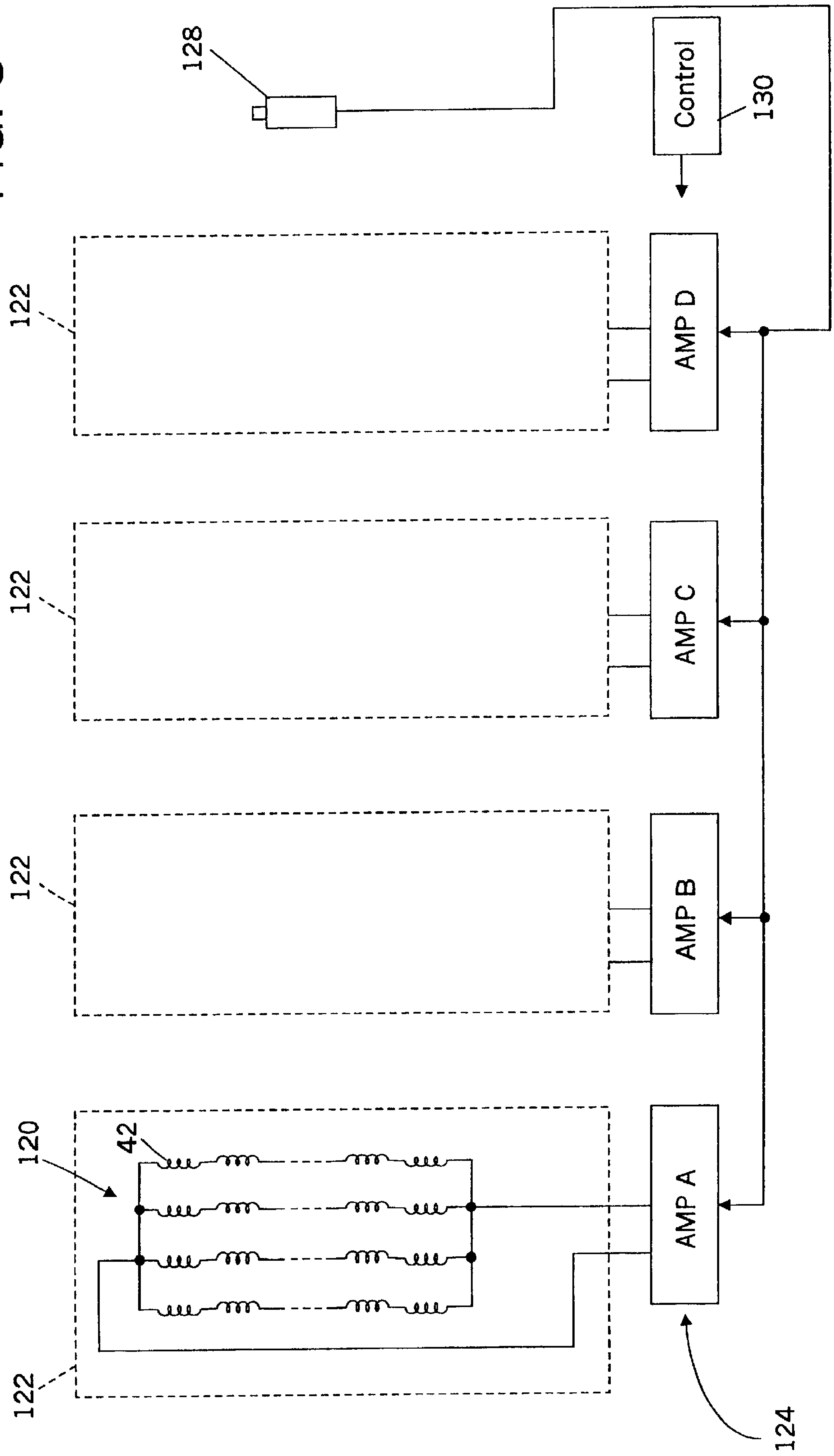


FIG. 9

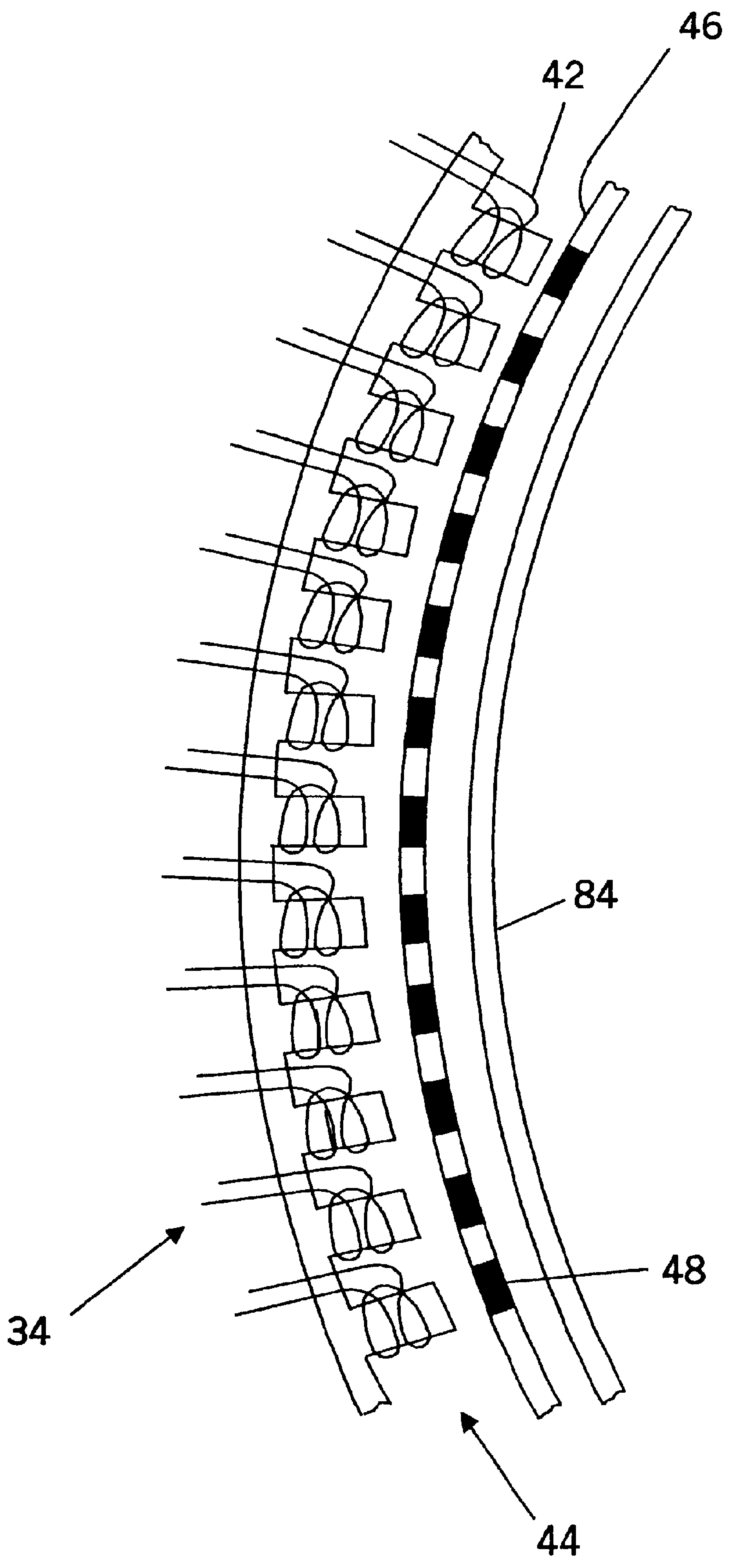


FIG. 10A

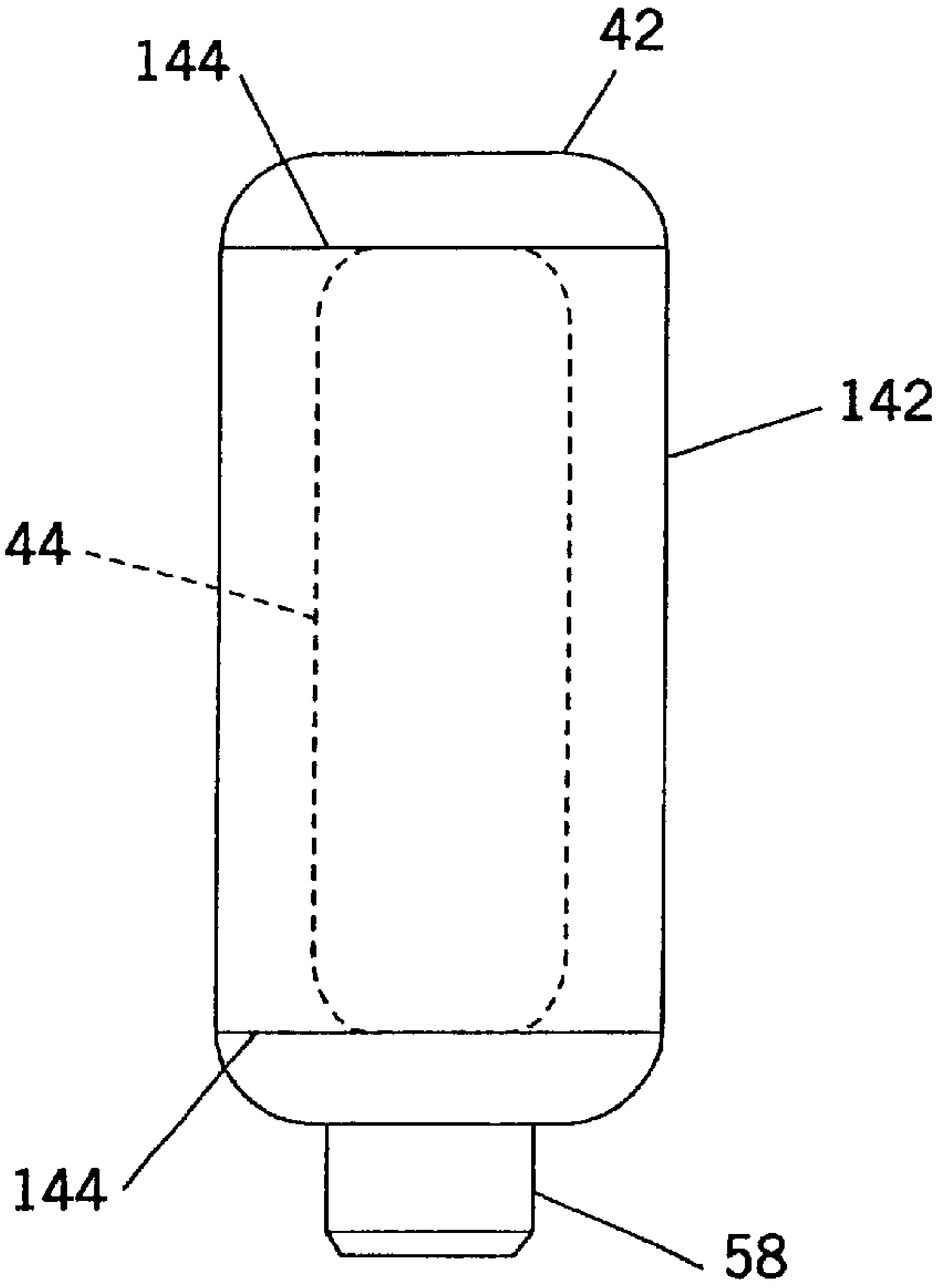
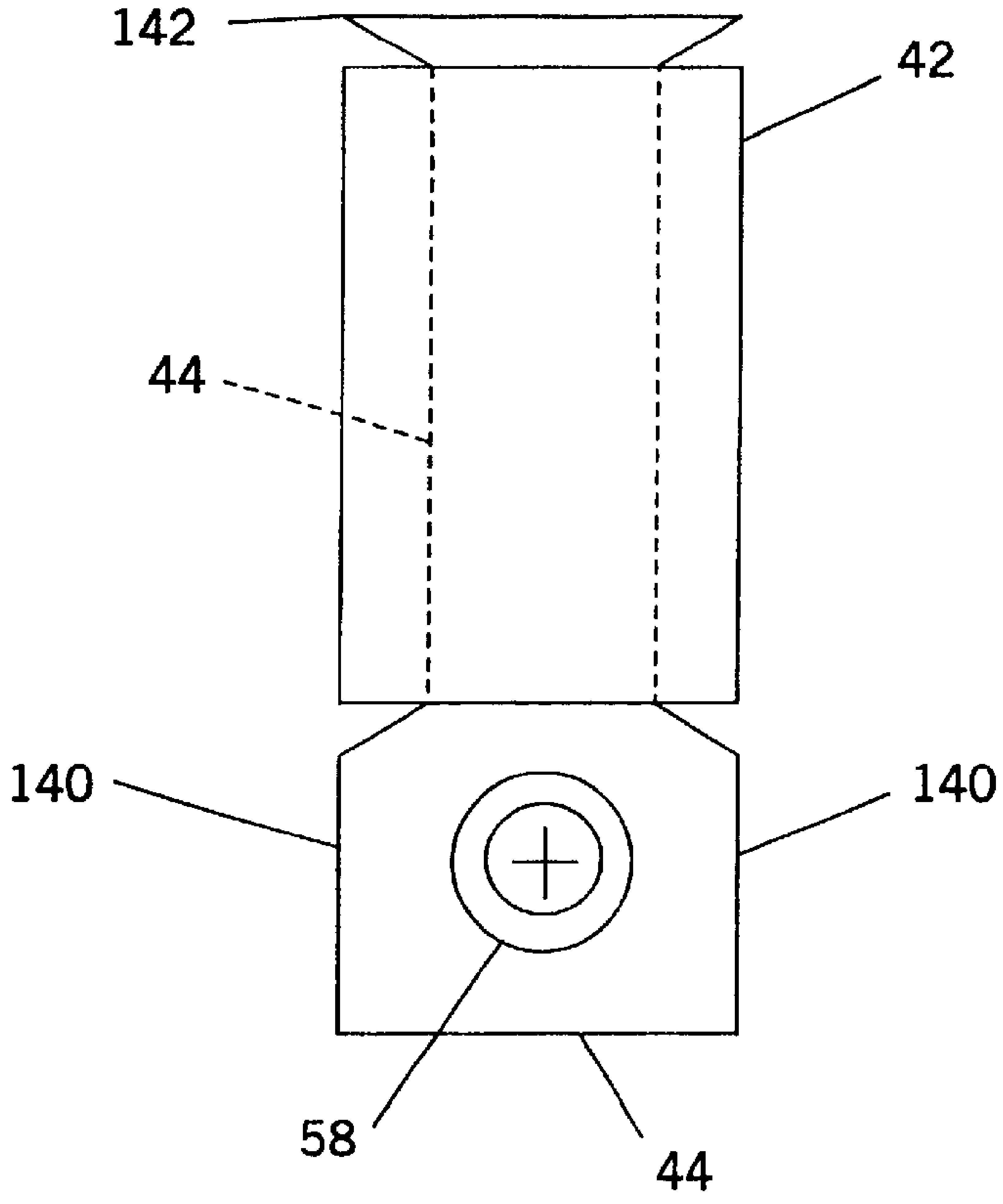


FIG. 10B



PERMANENT MAGNET PHASE-CONTROL MOTOR

This invention was made with U.S. Government support under Contract No. N00014-96-C-2079, awarded by the U.S. Navy. The Government has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates to a phase-shifting motor for rotary equipment and, more particularly, to an actively-controlled, permanent-magnet actuator for controlling an aspect of an item of rotating machinery by varying the phase of the motor rotor with respect to the rotation of the rotating machinery.

BACKGROUND OF THE INVENTION

Fundamental to the operation of many rotating machines, devices, or instrumentalities is the ability to control some aspect of the rotating portion of the instrumentality, device or machine. For example, many turbine or fan devices have facility for dynamically controlling the angle-of-attack of their rotor blades. Angle-of-attack is a factor in determining the dynamic forces acting on the blade and, hence, determining the forces applied by the blades to the frame of the instrumentality.

Control of blade angle-of-attack generally originates in the non-rotating frame of the instrumentality, rather than in the rotating coordinate reference frame of the rotating part of the instrumentality. For example, control of the variable pitch or the angle-of-attach of the blades of, for example, a wind turbine, a ship or airplane propeller, the main rotor or the torque-reaction fan or tail rotor of a helicopter are all originated within the frame of the instrumentality (e.g. the mast of a wind turbine, the airframe of an airplane or helicopter, or the engine room of a ship).

A method of bridging from the non-rotating frame to the rotating frame is required and many such bridging systems have been known for a long time. It is often a tricky mechanical engineering problem to introduce control signals or movements into a mechanism that is mounted on and turning with a rotating drive shaft. A common example of such a problem is controlling the pitch of the blades of a ship's screw propeller, an airplane propeller, a wind-driven turbine, or a helicopter's main lift rotor or torque reaction (tail) rotor. A related example is the control of leading or trailing edge flaps on either fixed pitch blades or on blades with controllable pitch.

U.S. Pat. No. 5,281,094, granted on Jan. 25, 1994, to McCarty, et al. discloses an arrangement for varying the pitch of fan blades. The blades are rotated by a main drive shaft which rotates a differential gearbox, and by rotating the gearbox, rotates the blades. A concentric shaft also enters the differential gearbox. The concentric shaft is normally locked so as to rotate with the main drive shaft. However, when the concentric shaft is unlocked, it is either rotated faster than the main drive shaft by an electric motor or braked by an electric brake so as to rotate slower than the main drive shaft. Relative rotation of the two shafts operates through the differential aspect of the gearbox in order to increase or decrease the pitch of the fan blades. When the desired blade pitch is attained, the two shafts are again locked together so as to rotate as one. U.S. Pat. No. 5,595,474, granted on Jan. 21, 1997, to Girard discloses a comparable mechanism.

As far back as the 1940s, in the helicopter art, U.S. Pat. No. 2,443,393, granted on Jun. 15, 1948, to Landgraf, disclosed a complex mechanical system for duplicating the effect of the cyclic pitch control of a helicopter by controlling trailing-edge flaps (ailerons) on the main rotor blades to affect maneuvering control of the craft.

U.S. Pat. No. 5,409,183, granted on Apr. 25, 1995, to Gunsallus, discloses using a computer with blade-response feedback and electric-to-hydraulic converters in order to control a leading-edge flap on a helicopter blade so as to affect instantaneous or cyclic blade pitch control.

U.S. Pat. No. 5,584,655, granted on Dec. 17, 1996, to Deering discloses affecting the instantaneous pitch or axis angle of a wind turbine blade by various means, in order to reduce excessive loadings due to gusty conditions.

U.S. Pat. No. 5,588,800, granted on Dec. 31, 1996, to Charles, et al. discloses the use of a trailing-edge flap near the tip of a helicopter main rotor blade to control blade vortex interaction noise.

In each of the above cases, complex arrangements are necessary to achieve the desired degree of control out at the end of a rotating shaft.

SUMMARY OF THE INVENTION

It is an object of the present invention to generate a mechanical control signal with respect to a rotating shaft from a signal source that is stationary with respect to the rotation of the shaft.

It is another object of the present invention to generate a mechanical control signal, with respect to a rotating shaft, using a transducer that occupies a minimum of axial space along the length of the rotating shaft.

It is yet another object of the present invention to generate a mechanical control signal, with respect to a rotating shaft, that is substantially equally effective at various rotational shaft speeds over the normal range of said rotational shaft speeds.

It is still yet another object of the present invention to generate a mechanical control signal, with respect to a rotating shaft, that is minimally subject to dynamic loads due to the speed of rotation of the shaft.

It is yet still another object of the present invention to generate a mechanical control signal, with respect to a rotating shaft, that is minimally subject to wear.

Still another object of the present invention is to generate a mechanical control signal, with respect to a rotating shaft, that requires a minimum of maintenance and adjustment.

Yet another object of the present invention is to generate a mechanical control signal, with respect to a rotating shaft, that operates at a rate that is at least of the same order of magnitude as the rotational speed of the shaft.

These and other objects and purposes are achieved by an electromagnetic actuator with rotor and stator portions, said rotor rotating substantially at the same average speed as the rotating shaft, with a plurality of alternately-reverse-pole permanent magnets at its perimeter and by a method of operating said actuator. A plurality of electromagnets on the stator are energized to develop a magnetic polarity of polarized areas adjacent to the poles of the permanent magnets and that reverses polarity at a frequency proportional to the rotational speed of the rotor each time that a permanent magnet on the rotor advances from one electromagnet to the adjacent electromagnet. The phasing of either the reversals or the magnitude of the energization of the electromagnetic devices being variable with respect to the rotation of the shaft so as to control the phasing of the instantaneous rotational position of the rotor with respect to the shaft, with linkage connecting the rotor to an instrumentality, for moving the instrumentality with respect to the shaft in response to a change in the phasing of the instantaneous rotational position of the rotor with respect to the shaft.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention will be had from the following detailed description when considered in connection with the accompanying drawings, wherein the same reference numbers refer to the same or corresponding items shown throughout the several figures, in which:

FIG. **1** is a schematic representation of applications of the present invention;

FIG. **2** is a schematic illustration, partially in cross section, of an embodiment of the present invention;

FIGS. **3**A, **3**B, **3**C, and **3**D are partial cross sectional views, in perspective, of a portion of the preferred embodiment of the present invention, in order to show greater exemplary detail of the construction of the preferred embodiment of the present invention;

FIG. **4** shows a partial view, taken in the direction of the axis of a rotating shaft of a machine with which the present invention might be used, showing one exemplary means for communicating to the rotating machine any phase change between the rotating shaft and the rotor or armature of the present invention;

FIG. **5** shows a partial view, taken in the direction of the axis of the rotating shaft of a machine with which the communicating means of FIG. **4** is preferably arranged about the rotating shaft;

FIG. **6** illustrates a phase communicating mechanism that is a mechanical equivalent alternative of that shown in FIG. **4**;

FIG. **7** is a block diagram of an exemplary electronic circuit for controlling the phase between the rotating shaft and the rotor or armature of the present invention;

FIG. **8** is a block diagram of an alternative electronic circuit for controlling the phase between the rotating shaft and the rotor or armature of the present invention;

FIG. **9** illustrates an alternative arrangement of the permanent magnets and the electromagnets of the motor of the present invention; and

FIGS. **10**A and **10**B illustrate the shape of the core and coil of the electromagnet of FIG. **3**, arranged to provide an efficient flux path.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Environment and Utility of the Present Invention

Referring now to the accompanying drawings and more particularly to FIG. **1**, there is shown an example of the environment with which the present invention would be useful. An instrumentality is shown such as the main rotary-wing lift rotor or torque reaction fan or tail rotor of a helicopter, a propeller or airscrew on a propeller-driven airplane, a wind turbine, or screw propeller on a watercraft. The propeller **20** conventionally has at least two blades **22** mounted at their inboard ends to a conventional hub **24**. The hub **24** rotates with a drive shaft **26** that is driven by or which drives a power device **28** which is conventionally a power source or a power sink and which rotates with the propeller **20** in order to accomplish the propeller's purpose.

The power device **28** is illustrated in FIG. **1** as comprising an engine **29** and a transmission **30**, as in a helicopter. However, the power device **28** could also be an electrical generator, in the case of the propeller **20** being used as a wind turbine.

While the term "propeller" is used with the reference number **20**, it will be understood by one having ordinary skill in the art that a turbine is an equivalent of a propeller for purposes of the present invention. It will also be evident to one having ordinary skill in the art that the apparatus shown schematically in FIG. **1** will ordinarily be on some conventional structure e.g., an airframe, a ship, a tower, etc. (represented by cross-hatch lines but not otherwise shown in FIG. **1**, for simplicity).

The blades **22** conventionally project on their own axes, outwardly from the hub **24**, in a direction substantially perpendicular to the axis of the drive shaft **26**. The blades **22** are also conventionally distributed uniformly about the perimeter of the hub **24**.

The blades **22** are of either of two conventional types, fixed pitch or variable pitch. Fixed-pitch blades are firmly attached to the hub **24**; and, as the shaft **26** rotates, the blades **22** tend to advance the same distance, relatively, through the medium within which they rotate. Variable pitch blades **22** are rotatably attached to the hub **24**, and can be rotated about their own axes with respect to the hub **24** so as to change their pitch in order to "bite" less or more of the environmental medium, depending on the pitch to which the blades have been adjusted. In the case of helicopters, the pitch of the blades can also be continuously varied by the cyclic or collective control so as to affect maneuvering of the helicopter.

A suggestion of a cyclic or a collective swash plate and control rods are shown in FIG. **1** only to illustrate the relative positions of the other components of the instrumentality. However, the cyclic or the collective swash plate and control rods are conventional and will not be described herein.

In addition or as an alternative, flaps **32** are placed on trailing edges of the blades **22** for any number of purposes (e.g., see the Landgraf patent, above). Alternatively, the flaps **32** can be placed on the leading edges of the blades **22** (e.g., see the Gunsallus patent, above).

Preferably, a motion transducer or motive device **34** is mounted about the drive shaft **26**. In this location, the motive device **34** can most advantageously coordinate its control operation with the rotational position of each blade **22** of the propeller **20**. Control signals are then conducted from the motive device **34** to the hub **24** along a communication path **36**. The communication path **36** can be hydraulic, mechanical, electrical or any other suitable transmission medium to carry control signals from the motive device **34** to the hub **24**. A logic system **38** controls the operation of the motive device **34** so as to generate the desired blade or flap movements at the appropriate angular positions of the blade about the drive shaft **26**.

A single motive device **34** (as illustrated in FIG. **1**), can be used to control all of the rotating parts of the instrumentality, e.g., the flaps **32** or the blades **22**, together. Alternatively, one control device can be used to control a single rotating part, flap, or blade. The several additional control devices such as **34***a* (equal in number to the number of flaps or rotor blades, for example) can be arranged one right next to the other (like pancakes) along the length of the drive shaft **26** in FIG. **1**.

Each motive device, e.g. **34**, conventionally has at least two parts, one part rotates with the drive shaft **26** (e.g., a rotor).

Another part (e.g., a stator) of the motive device **34** is mounted on the mounting structure and is substantially stationary with respect to the mounting structure.

If each motive device **34** is used to control the angle or pitch of a single flap **32** or blade **22**, it is possible for the effects of the several blades to be controlled individually. Therefore, the associated flap **32** or blade **22** can be changed as each blade moves with respect to the mounting structure and the medium through which it rotates. The flap **32** or blade **22** can then be changed back before completing a cycle of operation. Consequently, if the rotating portion of the instrumentality is a blade that moves relative to the medium through which it rotates (e.g., air), it is possible to reduce the noise and vibration generated by the interaction of the effects of the blades. For example, in the case of helicopter blades, it may be possible to reduce the noise and vibration conducted into or radiated from the helicopter. Additionally or alternatively, each motive device **34** (or **34***a*) can be used to control the angle of each flap **32** for some other purpose.

Simplified General Arrangement of the Preferred Embodiment

Referring now to FIG. **2**, the motive device **34** is schematically shown partially cut away and partially in cross section, in order to illustrate the general arrangement thereof. A frame **40** (the stator) is generally of a hollow, doughnut shape with the drive shaft **26** passing though the central hole thereof. The frame **40** can be made entirely of magnetically-permeable material. However, the frame **40** is preferably made of non-magnetic stainless steel or a light alloy such as aluminum including one or more magnetically-permeable inserts **41** where necessary. Preferably, as explained more fully, below, in connection with FIG. **10**, the bottom of each of a plurality of electromagnetic cores can be flared to contact or nearly contact its neighbor, so as to provide an efficient magnetic path.

Frame **40** preferably comprises at least one magnetically-permeable ring **41** so as to comprise the upper (as shown in FIG. **2**) portion of the magnetic return path for the several electromagnets. If needed, in order better to serve its magnetic purpose in the presence of rapidly-changing magnetic fields, the ring **41** and the electromagnetic cores can be made of laminated structures or even of electrically-insulated powdered structures.

A plurality of individual electromagnetic coils **42**, each with a central pole piece or core **44**, are circularly arranged about the inside of the frame **40**. Each pole piece **44** extends through the center of its associated coil **42** and is firmly mounted to the frame **40**.

A permanent magnet rotor or armature disk or ring **46** is located within the frame **40** and is freely rotatable with respect to the drive shaft **26**. A plurality of permanent magnets **48** are located about the perimeter of the rotor **46**, near the perimeter thereof. The permanent magnets **48** preferably have their opposite poles on either side of the rotor **46**, that is, up and down as viewed in FIG. **2**. The poles of each permanent magnet are oppositely polarized, relative to the permanent magnet on either side of it. That is, as the rotor **46** rotates, each permanent magnet is oppositely polarized with respect to the permanent magnet that preceded it and also with respect to the permanent magnet that succeeds it. For convenient, generic, definitional purposes, each permanent magnet **48** can be considered a permanently-magnetized region.

The rotor **46** is actually a ring that is thin with respect to its diameter. This gives the rotor **46** a relatively flat dimension along the axis or length of the drive shaft **26**. In rotating machinery, drive shaft length is normally to be minimized, wherever possible. Therefore, the stator housing **40** (FIGS. **2** and **3**) can also have a relatively flat dimension along the length of the drive shaft **26**, with the entire motive device **34** being almost disk-like, in appearance. Consequently, if necessary, several motive devices **34** can be mounted about the drive shaft **26** without necessitating an inordinate lengthening of the drive shaft. Such multiple control devices are illustrated by the second motive device **34** shown in dotted lines in FIG. **1**.

The rotor **46** is constructed so as to be relatively flat and fairly large in outside diameter, with a central opening therein which affords more than ample clearance between the rotor and the drive shaft **26**. The clearance between the inside edge **50** of the rotor **46** and the outside of the drive shaft **26** affords room for power, torque, or positioning take-off from the rotor **46**, as described below in connection with FIGS. **4**, **5**, **6**, and **7**.

In accordance with the present invention, the rotor **46** rotates at the average speed of the drive shaft **26**, changing only its angular or rotational phasing with respect to the driveshaft **26**. Two carrier plates **52**, which are firmly attached to the drive shaft **26**, rotate with the drive shaft. The rotor **46** is rotatably supported on bearings (for clarity, not shown in FIG. **2**, but shown in and described in connection with FIG. **3**), between the carrier plates **52**. Therefore, the rotor **46** is carried by the carrier plates **52** and associated bearings in a fixed axial and radial position with respect to the driveshaft **26** but free to rotate with respect to the driveshaft **26**.

There is a motion take-off (for clarity, not shown in FIG. **2** but shown in and described in connection with FIGS. **4**, **5**, **6**, and **7**) between the rotor **46** and the carrier plates **52**. This motion take-off mechanism can be a gear or lever system, a bowden wire, a hydraulic piston and cylinder, or any comparable means for transferring relative motion of the rotor **46** with respect to the carrier plates **52** via the communication path **36** (FIG. **1**) to the hub **24** for affecting the orientation of the blades **22** or the flaps **30**.

Detailed Construction of the Preferred Embodiment

Referring now to FIG. **3** (FIGS. **3**A, **3**B, **3**C, and **3**D), there is shown in greater detail, a partial view partially in cross section and partially in perspective, in order to illustrate the structure and construction of the preferred embodiment of the present invention. As shown in FIGS. **2** and **3** the motive device **34** is an electromagnetic actuator very generally in the form of a permanent magnet motor that comprises a rotor **46** having permanent magnets **48** and a stator or frame **40** having electromagnets **42** and **44**. As illustrated in FIG. **1**, the frame **40** of the motive device **34** is fixedly mounted co-axially with the driveshaft **26** of the instrumentality, e.g., with the propeller **20** of FIG. **1**. The motive device **34** is used to perform a control function within the instrumentality. Such control functions within rotating instrumentalities are typically performed mechanically.

The motive device of FIG. **3** is illustrated by gradual built-up stages, step-by-step, by progressing through FIGS. **3**A, **3**B, **3**C, and **3**D. Referring now to FIG. **3**A, the outer frame or stator housing **40** is shown having a base plate **54** and a side frame **56** that is mounted on and fastened to the base plate **54**. A plurality of electromagnet cores **44** are mounted on the side frame **56**, each by a screw **58**. An electrical coil **42** surrounds each electromagnetic core **44**.

The outer race of an anti-friction bearing **60** is clamped to the base plate **54** by a clamping ring **62**. The inner race of the anti-friction bearing **60** is clamped to the lower of the two carrier plates **52** (also shown more schematically in FIG. **2**), by a clamping ring **64**. The anti-friction bearing supports the periphery of the carrier plate **52** as it rotates with the shaft **26**, with respect to the stationary outer frame or stator housing **40**.

Referring now to FIG. **3**B, the coil **42** is shown in cross section, in a way meant to represent the individual wire-ends of the coil. The armature rotor ring **46** carries a plurality of permanent magnets **48**, which are arranged to pass over the upper ends (also shown more schematically in FIG. **2**) of the cores **44**, as the rotor ring **46** rotates about the axis of the shaft **26**. The outer race of an anti-friction bearing **66** is clamped to the rotor ring **46** by a clamping ring **68**.

The inner race of the anti-friction bearing **66** is supported by a structure (not shown) which is connected to the two carrier plates **52** and rotates therewith (see FIG. **3**D). By thus rotatably supporting the rotor **46** for only angular circumferential with respect to the shaft **26**, the rotor **46** is free to change its phase angle with respect to the shaft **26**, in order to apply motive force to the instrumentality that is to be moved, e.g., the flap near the end of the helicopter main rotor blade.

Referring now to FIG. **3**C, most of the structure of FIG. **3**B is shown. The lower of the two carrier plates **52** is shown further extending up and out, toward the rotor **46**. The upper of the two carrier plates **52** is also shown. It is the upper of the two carrier plates that has the depending structure (not shown) which supports the inner race of the anti-friction bearing **66**. Two inwardly-facing ears **70** are shown fastened to the rotor by two bolts **72**, only one of which is shown in FIG. **3**C. Each ear **70** has a mounting hole **74** at which the piston of a hydraulic power take-off cylinder can be rotatably attached. Similarly, any number of other types of mechanical or other power take-off devices can be attached (see FIGS. **4** and **5**).

Referring now to FIG. **3**D, most of the structure of FIG. **3**C is shown. The upper of the two carrier plates **52** is shown extended in the upward direction in order to engage the inner race of an anti-friction bearing **76**. The inner race of the anti-friction bearing **76** is clamped to the upper of the two carrier rings **52** by a clamping ring **78**. An upper cap ring **80** is fastened to the top of the side frame **56** and extends to the outer race of the anti-friction bearing **76**. A clamping ring **82** clamps the outer race of the anti-friction bearing **76** to the cap ring **80**. Since the cap ring **80** forms part of the outer frame or stator housing of the motive device **34**, the cap ring **80** is also stationary with respect to the rotating shaft and carrier plates **52**.

The first and preferred use of the present invention is expected to be in connection with transportation machines, and particularly with aircraft. Therefore, it is preferred that the base plate **54**, the side frame **56**, and cap ring **80** all be constructed of aluminum or some other lightweight material, not necessarily having magnetic properties. Consequently, a magnetic ring **84** is preferably fastened to the cap ring **80**, so as to be positioned above the permanent magnets **48**. The magnetic ring **84** provides a magnetic flux return path from the top of one permanent magnet to the top of the two adjacent permanent magnets. It will be remembered that the preferred arrangement of the permanent magnets **48** is such that adjacent permanent magnets shall be oriented in an alternating magnetic polar sense.

The electromagnetic cores **44** are magnetically interconnected by being flared at their lower ends (as described below, in connection with FIG. **10**).

The coils **42** are preferably connected in series, as described below and as depicted schematically in FIG. **8**. The coils **42** are wound and interconnected so that, with the same electrical current flowing through all of the coils, the magnetic poles of adjacent electromagnets are of opposite magnetic polarity. That is, the coils **42** are so interconnected that the electric currents through the coils **42** are so polarized that a magnetic flux is produced within each core **44** that is of opposite polarity to the polarity of the magnetic flux produced in the two adjacent cores. Therefore, the magnetic flux flowing in each core **44** is of the opposite polarity to its succeeding coil **42**, around the axis of the shaft **26**. As will be explained in more detail below, the polarity of the current flowing in the coils is rapidly reversed as the main driveshaft **26** of the instrumentality, e.g., the propeller **20** of FIG. **1**, rotates.

Another purpose for connecting all of the coils **42** in series is to make the magnetic flux flowing through all of the cores **44** as uniform as possible. That is, variation of flux flowing through the several cores **44** is to be minimized.

Positional Take-off From Rotor **46**

Relative rotational motion of the rotor **46** with respect to the carrier plates **52** and thus with respect to the driveshaft **26** is used to control the pitch of the blades **22** or the blade flaps **32** of the instrumentality or propeller **20** (FIG. **1**). The control linkage along the communication path **36** (FIG.**1**), between the rotor **46** and the carrier plates **52**, at one end, and the instrumentality at the other end, may be, for example, either hydraulic or mechanical.

One of the many possible positional take-offs from the rotor **46** is exemplified by the use of a hydraulic communication path **36** (FIG. **1**). Such a hydraulic positional take-off is shown schematically in FIG. **4**. A hydraulic master cylinder **90** is pivotally mounted to the carrier plates **52**. A piston (not separately shown) is located within the master cylinder **90**. A connecting rod **92** of the piston extends out of the end of the master cylinder **90** and is rotatably attached by a pivot pin to the inwardly-facing ears **70** through holes **74** (see FIG. **3**C).

As the shaft **26**, and with it the carrier plates **52**, and the rotor **46** change relative angular positions, the piston (not separately shown) moves within the cylinder **90**. The movement of the piston within the cylinder **90** forces hydraulic fluid to move through the hydraulic fitting(s) (not shown) of the cylinder **90**.

There is preferably one hydraulic hose or line (not shown) connected to the cylinder **90**, which comprises the communication path **36** of FIG. **1**. As described more fully below, in connection with FIG. **5**, there are preferably two cylinders **90** to develop hydraulic force to push the blade **22** or flap **32** in one direction; and there are two more cylinders **90** to push the blade **22** or flap **32** in the opposite direction. The use of four hydraulic cylinders **90** facilitates slimmer cylinder diameters, and the use of four cylinders offers better balancing of forces within the motive device **34**.

Alternatively, the hydraulic cylinder can be double acting to provide a push-pull, control of the blade or flap. As another alternative arrangement, with an appropriate biasing arrangement of the associated blade **22** or flap **32** (FIG. **1**), a single-acting hydraulic cylinder and a single line would be sufficient.

A four-cylinder hydraulic arrangement is illustrated schematically in FIG. **5**. Each of two reference ears **96** is preferably attached to both of the two carrier plates **52** (FIG. **3**D). A pair of hydraulic cylinders **90** is pivotally attached to each reference ear. The piston shafts **98** of a pair of hydraulic cylinders **90** are pivotally attached to each of the inwardly-facing ears **70** of the rotor **46** (FIG. **3**C).

As the rotor **46** moves in one direction with respect to the carrier plates **52**, the pistons of two of the hydraulic cylinders **90** are pushed deeper into the cylinders, forcing hydraulic fluid to flow under pressure in the associated hose or line (not shown) in the communication path **36**. Simultaneously, the pistons in the other two hydraulic cylinders **90** are partially withdrawn within their associated cylinders, thereby allowing space to accommodate the flow of hydraulic fluid thus displaced within the push-pull hydraulic system for moving the blades **22** or flaps **32** (FIG. **1**). When the rotor **46** moves in the opposite direction with respect to the carrier plates, the functioning of the two pairs of hydraulic cylinders **90** is exactly reversed, to move the blade **22** or flap **32** in the opposite direction.

Referring now to FIG. **6**, there is shown an alternative, mechanical embodiment to the hydraulic system depicted in FIGS. **4** and **5**. A bowden wire assembly **108**, such as a motorcycle brake or clutch cable, is shown with its outer, spiral sheath **110** conventionally clamped to a reference ear **96** of the carrier plates **52** (only a portion of which is shown in FIG. **4**). A communication rod **112** passes through the spiral sheath **110** and is pivotally attached to the inwardly-facing ears **70** of the rotor **46**.

The bowden wire **108** carries the positional signal through the communication path **36** (FIG. **1**). While the use of only one ear **70** and one bowden wire assembly **108** might be a less costly alternative, two ears are preferred. Two ears and bowden wire assemblies **108** would enable the use of a push pull arrangement to rotate the blade **22** or the flap **32** of FIG. **1**. A two-bowden-wire system for the communication path **36** is more likely to result in a more rigid and efficient mechanism.

Therefore, as the rotor **46** moves circumferentially with respect to the drive shaft **26** (FIG. **1**), to which the carrier plates **52** are firmly connected, the communication rod **112** slides longitudinally within the sheath **110** of the bowden wire **108**. Therefore, the bowden wire assembly **108** comprises the communication path **36** (FIG. **1**). Consequently, this movement of the rod **112** with respect to the sheath **110** is communicated to the associated blade **22** or flap **32** (FIG. **1**). As a result, the relative movement of the rod **112** inside the sheath **110** of the bowden wire assembly **108** changes the pitch of the associated blade **22** or moves the associated flap **32**.

Electrical Drive of the Electromagnetic Coils 42

The force which produces the relative motion of the permanent-magnet rotor **46** and the carrier plates **52** of the drive shaft **26** (FIGS. **2** and **3**) is derived from the interaction of the magnetic flux produced in the electromagnetic pole pieces **44** by reason of the electrical current in the non-rotating coils **42** with the magnetic field of the permanent magnets **48** on the rotating permanent-magnet-holding rotor **46**.

If the current in the coils **42** was in a constant direction and did not reverse polarity with the passage of each permanent magnet **48**, the direction of the force acting on the magnets would alternate as each successive (oppositely-polarized) permanent magnet passed over a given electromagnetic core **44**. This would produce no useful effect.

In order to achieve a force of controllable magnitude and sense so as to advance and retard the rotor **46** with respect to the driveshaft **26**, the direction of the current passing through the coils **42** is reversed as each permanent magnet **48** passes over a pole piece **44**. This commutation is accomplished by a switching amplifier that is triggered by one or more conventional position sensors, which sense the movement of the rotor with respect to the pole pieces **44**. The preferred position sensor is one or more coils or other type of magnetic flux sensor. Such magnetic flux sensors should preferably be fixed with respect to the electromagnetic coils **42**. Alternatively, the voltage generated in one or more electromagnet coils **42** by the passage of the permanent magnets **48** over the pole pieces **44** can be used to trigger a reversal of the current in the electromagnet coils **42**. As an alternative type of rotor position sensor, any of a plurality of non-magnetic types of sensors can be used, such as an optical sensor.

When a permanent magnet **48** passes the sensor (either one of the coils **42** or a separate sensor), the output from the sensor is used to determine both the timing or phasing of the passage of the permanent magnet and its magnetic polarity. The output of the sensor is then conventionally used to signal one or more electronic power switching amplifiers to reverse the direction of the current in the coils **42**. The only requirement of such amplifiers is to deliver the desired magnitude of current to the coils in the proper polarity and to switch that polarity at the proper instant.

In the example of the blade **22** and the flap **32**, the fluid passing over the propeller blade **22** will bias the flap **32** to the neutral or center position, aligned with the adjacent edge of the blade. The relative rotation of the rotor **46** and the shaft **26** will tend to drive the flap **32** either up or down with respect to the trailing edge of the blade **22**.

The polarity of the current in the coils **42** is always switched exactly as the center of the permanent magnet **48** is aligned with the center of the pole piece **44**. The electrical and magnetic power to either advance or retard the rotor **46** with respect to the drive shaft **26** is the magnitude of the current in the coil **42**.

A high current just after the permanent magnet **48** passes the pole piece **44** will repel the permanent magnet from the pole piece just passed and pull the permanent magnet toward the next pole piece. By thus urging the permanent magnet, and with it the rotor **46**, forward, the rotor **46** will tend to advance with respect to the drive shaft **26**.

To retard the rotor with respect to the drive shaft **26**, acting upon the blade **22** or the flap **32**, the electric current through the coil **42** is so polarized to retard the rotor **46** with respect to the drive shaft **26**. That is, the polarity of the current in the coil **42** is selected to pull the permanent magnet against its motion to leave the pole piece or core **44**. Also, that same polarity of the current in the coil **42** tends to push against and thus retard the next permanent magnet that is approaching the coil and its core **44**.

The above control of current amplitude and polarity to move the rotor **46** forward or backward with respect to the shaft **26** is the preferred mode of use of the present invention

It is possible, as an alternative embodiment and mode of use of the present invention, for the rotor **46** to be biased to the retarded or advanced condition, with respect to the drive shaft **26**, as by aerodynamics, spring, or other loading of the blade **22** or the flap **32** (FIG. **1**). That bias loading can be either in the direction to retard or to advance the rotor **46**. In such a case, simply weakening the strength of the coil current and thus the electromagnetic field, will allow a retarding bias or an advancing bias to retard or to advance the rotor **46** with respect to the drive shaft **26**.

It will be evident to a person having ordinary skill in the art that, as the rotor **46** advances or is retarded, the phasing of the center of each permanent magnet **48** also advances or is retarded, with respect to the shaft **26**. The moment when the center of a permanent magnet crosses the center of a pole piece **44** marks the point at which the current through the coils **42** is reversed. Therefore, the phasing of the reversals of the energizing polarity of the electromagnets also varies with respect to the rotation of the shaft **26**. Consequently, as the phasing of the energizing current reversals in the coils **42** changes, with respect to the shaft **26**, that phasing translates directly in to control of the associated parameter of the instrumentality **20**.

Referring now to FIG. **7**, there is shown a block diagram of an exemplary circuit for operating the control device (permanent magnet motor) **34**. In the preferred embodiment of the present invention, there is a large number of coils, magnetic cores, and permanent magnets. Since the electrical current in the coils that drive the rotor **46** are preferably reversed simultaneously, they are preferably all connected in series, so that the same current flows through each coil, thereby maximizing the uniformity of coil energization. However, amplifiers strong enough (high voltage capability) to drive so many magnetic coils in series are not readily available, especially in inexpensive, integrated-circuit form.

Alternatively, the coils could all be connected in parallel. This would require an amplifier with only modest voltage capability but with very high current capability. Also, it is expected that uniformity of coil excitation may be compromised over a series connection.

Therefore, in an effort to achieve a practical application, a compromise is preferred, as illustrated in FIG. **7**. Eleven coils **42** are connected in series to form a string **120** of series-connected coils. Four strings **120** are connected in parallel to make up a coil block **122**. There are three blocks of forty-four coils, each. Each of the three coil blocks is connected to the output of an amplifier **124** (AMPs A, B, and C).

The last forty-four coils are divided in half. Two strings **120** are connected in series and are used as a rotor position sensor **126**, the output of which is used to trigger the amplifiers **124** to reverse the current in the other coils. The other two strings are connected in parallel and connected to the output of a fourth amplifier **124** (AMP D). The output of the fourth amplifier is adjusted to recognize that it is only energizing two strings of coils. The arrangement of FIG. **7** is a compromise which sacrifices the outputs of two strings of coils in an effort to obtain ample sensor signal strength to trigger the amplifiers **124**.

FIG. **8** illustrates another alternative compromise which also uses strings **120** of eleven series-connected coils **42**. Four strings **120** are connected in parallel to form one coil block **122**. However, four of the coil blocks **122** are connected to the four amplifiers **124**. A separate sensor **128** provides the rotor-position information to trigger the four amplifiers **124**.

The movement of the rotor **46** relative to the shaft **26** can be very simply controlled by merely moving the sensor **128** angularly within the housing of the motive device **34**. Alternatively, the magnitude of the current driving the coils **42** can be increased or decreased in order to move the rotor **46** relative to the shaft **26**. Such control can be realized by the use of an appropriate controller **130** which controls the output of all four of the amplifiers **124**.

However, for a more complex environment such as controlling the position of a noise-and-vibration-attenuating flap **32** on a blade **22** of the main lift rotor of a helicopter, the controller **130** is preferably a conventional stored program computer or some other form of electronic signal processor. For such a more complex purpose, the controller would automatically control the amplitude of the output of the amplifiers **124** based upon its programmed response to the outputs of one or any number of noise and vibration sensors (not shown) at locations throughout the helicopter.

The above description and FIGS. **7** and **8** illustrate connection of the coils **42** in series and/or parallel, using four amplifiers **124**. However, it will be evident to a person having ordinary skill in the art that there would be an equivalent result if the coils **42** were all connected in series or parallel or if each coil **42** were connected to its own amplifier, each amplifier being driven in the same manner as the amplifier **124**.

A propeller blade **22** or a flap **32** (FIG.**1**) is either biased to one extreme orientation or is completely unbiased. If unbiased, the control device and the amplifiers **124** are preferably arranged to swing the blade or flap in either direction from an assumed neutral position by the polarity and amplitude of the output of the amplifiers **124**.

In realistic operation, there is usually some aero- or hydro-dynamic tendency to center the blade **22** or the flap **32** to a centered or neutral orientation or position, from which the motive device **34** displaces it in at least one or either direction. The direction of blade or flap displacement from its neutral position is controlled by the polarity of the output of the amplifier **124**. Similarly, the extent of movement of the propeller blade **22** or the flap **32** from its center or neutral position is related to the amplitude, timing, or magnitude of the output of the amplifier **124**.

Alternatively, the blade **22** or the flap **32** can be biased toward one of its extreme positions. In that case, the motive device **34** (FIG. **1**) normally pulls the blade **22** or the flap **32** toward its opposite extreme position, against its bias force. That bias force can be provided by a spring or by aero- or hydro-dynamic forces, etc.

Radial Magnetic Orientation

Referring now to FIG. **9**, there is illustrated an alternative orientation of the permanent magnets **48** and the electromagnet coils **42**. The rotor **46** has a plurality of permanent magnets **48** positioned around its periphery, with their flux paths oriented radially, rather than axially, as shown in FIGS. **2** and **3**. The electromagnetic core structure **44** can be of unitary construction around the entire circumference of the inside of the motive device **34**. Alternatively, there can be arcuatly-shaped segments of electromagnetic cores placed around the inside of the motive device **34**. As another alternative, the core structure **44** could involve individual cores **44**, each positioned in close proximity to its neighbor, as illustrated in FIG. **3**A.

Coils **42** are placed or wound around each core element that projects radially inward toward the rotor **46**. Permanent magnets **48** are placed at appropriate intervals around the periphery of the rotor **46**, such that their flux paths are oriented radially, with each permanent magnet oriented in the opposite polar sense to its two adjacent neighbors.

A magnetic ring **84** is placed just radially inward of the rotor **46**, in order to provide a flux path on the side of the permanent magnets on the side opposite the pole pieces or core structures **44**. The magnetic ring **84** can be an integral part of the rotor **46**. However, if the mass of the rotor **46** is to be minimized, the magnetic ring **84** can be mounted integral with one of the carrier plates **52**, but in immediate proximity to the rotor **46**. Alternatively, the magnetically-permeable ring **84** can also be mounted in a fixed relationship with respect to the pole pieces or cores **44**, as with the magnetically-permeable ring **41** of FIG. **2** and **84** of FIG. **3**D.

The arrangement illustrated in FIG. **9** can also be turned inside out, with the pole pieces or cores **44** being radially inside of the rotor **46** and with the magnetically-permeable ring **84** being radially outside of the rotor **46**.

In every other respect, the arrangement illustrated in FIG. **9** is the same as the arrangement illustrated in FIGS. **2** and **3**.

Construction of Magnetic Cores **44** with Coils **42**

FIGS. **10**A and **10**B are provided in an effort to promote a better understanding of the nature of the flux return paths through the several cores **44** placed about the periphery of the inside of the motive device **34**, as shown in FIG. **3**A. FIG. **10**B shows the front view of the core **44** with the coil **42** wrapped around the core. The front view (FIG. **10**B) better shows the coil **42** in place about the pole piece or core **44**. The screw **58**, which holds the core **44** in place inside the motive device **34**, is also shown in both FIGS. **10**A and **10**B.

The pole piece or core **44** is waisted to accommodate the coil **42**. However, the core **44** flares out at its end **142**, proximate the permanent magnet (not shown in FIG. **10** but shown in FIG. **3**B), in order to maximize the area of the air gap—and thus the magnetic flux—between the core and the permanent magnet. By maximizing the area of the flux path at the air gap between the core **44** and the permanent magnet **48**, greater magnetic attraction and repulsion can be achieved for a given amount of electrical excitation of the coil **42**.

The core **44** is wider at its base, where it is held to the inside of the motive device **34**. The two sides **140** of the core **44** project out at least as wide as the outside of the coil **42**. Those two sides **140** are intended to be positioned as close to the sides of the adjacent cores as manufacturing tolerances will allow. The sides **140** of the core **44** are preferably not tapered to accommodate the radial angle of the inside of the motive device **34**. The taper would be very slight and preferably not worth the expense, in view of the relatively large area of the sides **140** and the slight thickness of the air gap between adjacent cores.

The flared-out portion **142** of the top of each core **44** is flared out to a width slightly less than that of the sides **140**. Also, the flared-out portion **142** of the top of the core **44** extends for a length only as far—in the direction of the axis of the screw **58**—as is necessary to match the radial length of the adjacent permanent magnet **48**. That length of the flared-out portion **142** is also the length of the core **44** in the direction of the axis of the screw **58**, as indicated by two solid lines **144** in FIG. **10**A. That length is also seen in FIG. **3**B.

The flared-out portions **142** flare to a fairly sharp edge so as to minimize the flux leakage between adjacent cores **44**. Such flux leakage between adjacent cores **44** constitutes a partial magnetic short circuit, since any such leaked flux between the tops of adjacent cores **44** reduces the amount of magnetic flux that can exert a circumferential force upon the permanent magnets **48** and thus the rotor **46**.

While the form of the apparatus and method steps herein described constitute a preferred embodiment of the present invention, it is to be understood that the invention is not limited to this precise form of either the apparatus or method disclosed herein and that changes may be made therein without departing from the scope of the invention which is defined in the appended claims.

What is claimed is:

1. An electromagnetic actuator with a rotor portion having an axis and a perimeter and having a stator portion, said rotor portion rotating substantially at the same speed as a rotating shaft, for actuating control of an instrumentality rotated with said shaft by one of a relative position, juxtaposition, or phasing relationship between said rotor and said shaft, said electromagnetic activator comprising:

a plurality of permanently-magnetized regions located proximate the perimeter of said rotor portion, said permanently magnetized regions being polarized so that adjacent permanently magnetized regions about the perimeter of the rotor are of opposite magnetic polarity;

a plurality of electromagnets each having a core and a coil surrounding the core mounted on the stator and positioned proximate the permanently magnetized regions, said electromagnets being subject to energization so that adjacent poles of said cores are of opposite magnetic polarity;

the energization of the electromagnets causing a reversal of polarity at a frequency proportional to the rotational speed of the rotor, such that the cores reverse polarity each time that a permanently magnetized region on the rotor advances from being proximate one core to being proximate the adjacent core;

the phasing of the reversals of the energizing polarity of the electromagnets being variable with respect to the rotation of the shaft so as to control the phasing of the instantaneous rotational position of the rotor with respect to the shaft; and

a linkage means for extracting a relative-position signal from the juxtaposition of said rotating shaft and said rotor portion for affecting said instrumentality.

2. An electromagnetic actuator according to claim **1** wherein said rotor is generally disk-shaped, with a thickness in the axial direction of the rotor that is substantially less than the peripheral diameter of the rotor.

3. An electromagnetic actuator according to claim **2** wherein the magnetic flux path of said permanently magnetized regions is in a direction substantially parallel with the axis of the rotor.

4. An electromagnetic actuator according to claim **2** wherein the magnetic flux path of said permanently magnetized regions is in a direction substantially perpendicular to the axis of the rotor.

5. An electromagnetic actuator according to claim **1** wherein said rotor is arranged substantially coaxial with said shaft.

6. An electromagnetic actuator according to claim **1** wherein said stator substantially surrounds said rotor and a portion of said shaft.

7. An electromagnetic actuator according to claim **6** wherein said electromagnets are positioned within the stator, adjacent to the perimeter of the rotor and remote from the shaft.

8. An electromagnetic actuator according to claim **1** further comprising a sensor for sensing the rotational position of the rotor.

9. An electromagnetic actuator according to claim **8** further comprising means for reversing the energization of said electromagnets each time that a permanently-magnetized region coincides with a location of a core.

10. A method of actuating control of an instrumentality rotating with a shaft, using an electromagnetic actuator with a rotor portion normally rotating substantially at the same speed as the shaft and having a plurality of permanent magnets mounted in proximity to the periphery of said rotor and being arranged with alternate polarity around the rotor and having a stator with a plurality of electromagnets each having a core and a coil surrounding the core mounted thereon for cooperation with the permanent magnets, the method comprising:

applying electric current to said electromagnets so as to produce alternate polarity therein in a pattern substantially to cooperate with the permanent magnets;

reversing the direction of electrical current through the electromagnets as the rotor advances from electromagnet to electromagnet, in order to apply a magnetically-induced force to each permanent magnet by its instantaneously associated electromagnet;

changing the timing relationship between the reversal of the electrical current through the electromagnets and the movement of the shaft so as to change the timing of the application of electromagnetic force on the rotor with respect to the shaft in order to affect the phase relationship between the rotor and the shaft; and

communicating to the instrumentality the difference in phase between the rotor and the shaft as a mechanical motion within the instrumentality.

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